

Axino - New Candidate for Cold Dark Matter¹

Leszek Roszkowski^{1,2}

¹*Department of Physics, Lancaster University, Lancaster LA1 4YB, England*

²*TH Division, CERN, CH-1211 Geneva 23, Switzerland*

Abstract

Supersymmetric extensions of the Standard Model when combined with the Peccei-Quinn solution to the strong CP problem necessarily contain also the axino, the fermionic partner of the axion. In contrast to the neutralino and the gravitino, the axino mass is generically not of the order of the supersymmetry breaking scale and can be much smaller. The axino is therefore an intriguing candidate for a stable superpartner. The axinos are a natural candidate for cold dark matter in the Universe when they are generated non-thermally through out-of-equilibrium neutralino decays or via a competing thermal production mechanism through scatterings and decays of particles in the plasma. We identify axino masses in the range of tens of MeV to several GeV (depending on the scenario) as corresponding to cold axino relics if the reheating temperature T_R is less than about 5×10^4 GeV. At higher T_R and lower mass, axinos could constitute warm dark matter. In the scenario with axinos as stable relics the gravitino problem finds a natural solution. The lightest superpartner of the Standard Model spectrum will remain stable in high-energy detectors but may be either neutral or charged. The usual constraint $\Omega_\chi h^2 \lesssim 1$ on the relic abundance of the lightest neutralino does not hold.

CERN-TH/2001-059

February 2001

¹Based on invited plenary talks at the 4th International Workshop on Particle Physics and the Early Universe (COSMO-2000), Cheju, Cheju Island, Korea, September 4–8, 2000 and the 3rd International Workshop on the Identification of Dark Matter (IDM-2000), York, England, 18–22 September 2000.

1 Introduction

The nature of dark matter (DM) in the Universe remains unknown. Its relic abundance is probably in the range $0.1 \lesssim \Omega_\chi h^2 \lesssim 0.3$ or so and is most likely “cold”. It presumably consists for the most part of some weakly interacting massive particles (WIMPs).

WIMPs do not necessarily have to interact via weak interactions *per se*. Very much weaker interaction strengths can also lead to interesting cosmological abundances. One expects that they should preferably be electrically and color neutral, and therefore be non-baryonic, otherwise they would dissipate their kinetic energy.

Supersymmetry (SUSY) provides a natural context for WIMPs. In the presence of R -parity, the (massive) lightest supersymmetric particle (LSP) is stable and may substantially contribute to the relic mass density. It may therefore constitute the DM in the Universe. Among SUSY WIMPs, the neutralino remains the most popular choice by being perhaps the most “genuine” WIMP. The gravitino is another interesting candidate although it generically suffers from the (in)famous “gravitino problem”.

Recently, it has been pointed out[1, 2] that another well-motivated SUSY particle can be a plausible cold DM (CDM) candidate. The particle in question is the axino, a fermionic SUSY partner of the axion. Axionic particles arise naturally in various superstring models and, historically first, in the Peccei-Quinn (PQ) solution to the strong CP problem.

It is also well-justified to consider the axino as the LSP since its mass is basically a free parameter which can only be determined in specific models. Since current LEP bounds on the neutralino are in excess of 32 GeV, or so, it becomes increasingly plausible that there may well be another SUSY particle which is lighter than the neutralino, and therefore a candidate for the LSP and dark matter. The axino is just such a candidate.

In this talk I will first describe the main properties of the new candidate. Next I will discuss ways of producing axinos in the early Universe and the expected abundance. Finally, I will make some remarks about the ensuing implications for cosmology and phenomenology.

2 Axino

Axino is a superpartner of the axion pseudoscalar. It is thus a neutral, R -parity negative, Majorana chiral fermion. There exist several SUSY and supergravity implementations of the well-known original axion models (KSVZ[3] and DFSZ[4]). (Axion/axino-type supermultiplets also arise in superstring models.) In studying cosmological properties of axinos, we will concentrate on KSVZ and DFSZ-type models where the global $U(1)$ PQ symmetry is spontaneously broken at the PQ scale f_a . A combination of astrophysical (white dwarfs, *etc*) and cosmological bounds gives $10^9 \text{ GeV} \lesssim f_a \sim 10^{12} \text{ GeV}$ [5] although the upper bound can be significantly relaxed if inflation followed the decoupling of primordial axionic particles and the reheating temperature $T_R \ll f_a$.

The two main parameters of interest to us are the axino mass and coupling. The mass $m_{\tilde{a}}$ strongly depends on an underlying model and can span a wide range, from very small ($\sim \text{eV}$) to large ($\sim \text{GeV}$) values. What is worth stressing is that, in contrast to the neutralino and the gravitino, axino mass does not have to be of the order of the SUSY breaking scale in the visible sector, $M_{\text{SUSY}} \sim 100 \text{ GeV} - 1 \text{ TeV}$ [6, 7, 8]. The basic argument goes as follows. In the case of unbroken SUSY, all members of the axion supermultiplet remain degenerate and equal to the tiny mass of the axion given by the QCD anomaly. Once SUSY is softly broken, superpartners acquire mass terms. Since the axino is a chiral fermion, one cannot write a dimension-four *soft* mass term for the axino. (For the same reason there are no soft terms for, *e.g.*, the MSSM higgsinos.) The lowest-order term one can write will be a non-renormalizable term of dimension-five. The axino mass will then be of order $M_{\text{SUSY}}^2/f_a \sim 1 \text{ keV}$ [6, 8].

However, in specific SUSY models there are normally additional sources of axino mass which can generate much larger contributions to $m_{\tilde{a}}$ at one-loop or even the tree-level. One-loop terms will always contribute but will typically be $\lesssim M_{\text{SUSY}}$ (KSVZ) or even $\ll M_{\text{SUSY}}$ (DFSZ). Furthermore, in non-minimal models where the axino mass eigenstate comes from more than one superfield, $m_{\tilde{a}}$ arises even at the tree-level. In this case $m_{\tilde{a}}$ can be of order M_{SUSY} but can also be much smaller. In a study of cosmological properties of axinos, it therefore makes sense to treat their mass as a basically free parameter.

Axino couplings to other particles are generically suppressed by $1/f_a$. For our purpose the most important coupling will be that of axino-gaugino-gauge boson interactions which can be written as a dimension-five term in the Lagrangian

$$\mathcal{L}_{\tilde{a}\lambda A} = i \frac{\alpha_Y C_{aYY}}{16\pi (f_a/N)} \tilde{a} \gamma_5 [\gamma^\mu, \gamma^\nu] \tilde{B} B_{\mu\nu} + i \frac{\alpha_s}{16\pi (f_a/N)} \tilde{a} \gamma_5 [\gamma^\mu, \gamma^\nu] \tilde{g}^b F_{\mu\nu}^b, \quad (1)$$

where \tilde{B} denotes the bino, the fermionic partner of the $U(1)_Y$ gauge boson B , which is one of the components of the neutralino, \tilde{g} stands for the gluino and $N = 1(6)$ for the KSVZ (DFSZ) model. One can show that the $SU(2)_L$ coupling can be rotated away so long as one discusses cosmological properties of the axino at large temperatures. Depending on a model, one can also think of terms involving dimension-four operators coming, *e.g.*, from the *effective* superpotential $\Phi\Psi\Psi$ where Ψ is one of MSSM matter (super)fields. However, axino production processes coming from such terms will be suppressed at high energies relative to processes involving Eq. (1) by a factor $m_{\tilde{\Psi}}^2/s$ where s is the square of the center of mass energy. We will comment on the role of dimension-four operators again below but, for the most part, mostly concentrate on the processes involving axino interactions with gauginos and gauge bosons, Eq. (1), which are both model-independent and dominant.

3 Axino Production

Particles like axinos and gravitinos are somewhat special in the sense that their interactions with other particles are very strongly suppressed compared to the SM interaction strengths. Therefore such particles remain in thermal equilibrium only at very high temperatures. In the particular case of axinos (and axions), their initial thermal populations decouple at [7] $T_D \sim 10^{10}$ GeV. At such high temperatures, the axino co-moving number density is the same as the one of photons. In other words, such primordial axinos freeze out as *relativistic* particles. Rajagopal, Turner and Wilczek (RTW) [7] pointed out that, in the absence of a subsequent period of inflation, the requirement that the axino energy density is not too large ($\Omega_{\tilde{a}} \lesssim 1$) leads to $m_{\tilde{a}} < 2$ keV and the corresponding axinos would be light and would provide warm or even hot dark matter [7]. We will not consider this case in the following primarily because we are interested in cold DM axinos. We will therefore assume that the initial population of axinos (and other relics, like gravitinos) present in the early Universe was subsequently diluted away by an intervening inflationary stage and that the reheating temperature after inflation was smaller than T_D . It also had to be less than f_a , otherwise the PQ would have been restored thus leading to the well-known domain wall problem associated with global symmetries.

In order to generate large enough abundance of axinos, one needs to repopulate the Universe with them. There are two generic ways of doing achieving this. First, they can be generated through thermal production, namely via two-body scattering and decay processes of ordinary particles and sparticles still in thermal bath. (Despite the name of the process, the resulting axinos will typically be already out-of-equilibrium because of their exceedingly tiny couplings to ordinary matter.) Second, axinos may also be produced in decay processes of particles which themselves are out-of-equilibrium. Such particles could for example be ordinary superpartners, the gravitino or the inflaton field. (By “ordinary” we mean a particle or its superpartner carrying only Standard Model quantum numbers.) Below we will concentrate on the first possibility in the case the decaying neutralino.

3.1 Thermal Production

After inflation the Universe can be re-populated with axinos (and gravitinos) through scattering and decay processes involving superpartners in thermal bath. As long as the axino co-moving number density $n_{\tilde{a}}$ is much smaller than n_γ , the number density of photons in thermal equilibrium, its time evolution will be adequately described by the Boltzmann equation

$$\frac{dn_{\tilde{a}}}{dt} + 3Hn_{\tilde{a}} = \sum_{i,j} \langle \sigma(i + j \rightarrow \tilde{a} + \dots) v_{\text{rel}} \rangle n_i n_j + \sum_i \langle \Gamma(i \rightarrow \tilde{a} + \dots) \rangle n_i. \quad (2)$$

Here H is the Hubble parameter, $H(T) = \sqrt{\frac{\pi^2 g_*}{90 M_{\text{P}}^2}} T^2$, where g_* is the effective relativistic degrees of freedom, $\sigma(i+j \rightarrow \tilde{a} + \dots)$ is the scattering cross section for particles i, j into final states involving axinos, v_{rel} is their relative velocity, n_i is the i th particle number density in thermal bath, $\Gamma(i \rightarrow \tilde{a} + \dots)$ is the decay width of the i th particle and $\langle \dots \rangle$ stands for thermal averaging. (Averaging over initial spins and summing over final spins is understood.) Note that on the *r.h.s.* we have neglected inverse processes since they are suppressed by $n_{\tilde{a}}$.

The main axino production channels are the scatterings of (s)particles described by a dimension-five axino-gaugino-gauge boson term in the Lagrangian (1). Because of the relative strength of α_s , the most important contributions will come from 2-body strongly interacting processes into final states involving axinos, $i + j \rightarrow \tilde{a} + \dots$. (Scattering processes involving electroweak interactions are suppressed by both the strength of the coupling and a smaller number of production channels[2].) The cross section can be written as

$$\sigma_n(s) = \frac{\alpha_s^3}{4\pi^2 (f_a/N)^2} \bar{\sigma}_n(s) \quad (3)$$

where \sqrt{s} is the center of mass energy and $n = A, \dots, K$ refers to different channels which are listed in Table I in Ref. [2]. The diagrams listed in the Table are analogous to those involving gravitino production and we use the same classification. This analogy should not be surprising since both particles are neutral Majorana superpartners.

In addition to scattering processes, axinos can also be produced through decays of heavier superpartners in thermal plasma. At temperatures $T \gtrsim m_{\tilde{g}}$ these are dominated by the decays of gluinos into LSP axinos and gluons. The relevant decay width is given by

$$\Gamma(\tilde{g}^a \rightarrow \tilde{a} + g^b) = \delta^{ab} \frac{\alpha_s^2}{128\pi^3} \frac{m_{\tilde{g}}^3}{(f_a/N)^2} \left(1 - \frac{m_{\tilde{a}}^2}{m_{\tilde{g}}^2}\right)^3 \quad (4)$$

and one should sum over the color index $a, b = 1, \dots, 8$. At lower temperatures $m_{\chi} \lesssim T_{\text{R}} \lesssim m_{\tilde{g}}$, neutralino decays to axinos also contribute while at higher temperatures they are sub-dominant. They only become important when the axino yield

$$Y_{\tilde{a}}^{\text{TP}} = \frac{n_{\tilde{a}}^{\text{TP}}}{s}, \quad (5)$$

where $s = (2\pi^2/45)g_{s*}T^3$ is the entropy density, and normally $g_{s*} = g_*$ in the early Universe, becomes too small to be cosmologically interesting.

The results are presented in Fig. 1 for representative values of $f_a = 10^{11}$ GeV and $m_{\tilde{q}} = m_{\tilde{g}} = 1$ TeV. The respective contributions due to scattering as well as gluino and neutralino decays are marked by dashed, dash-dotted and dotted lines.

It is clear that at high enough T_{R} , much above $m_{\tilde{q}}$ and $m_{\tilde{g}}$, scattering processes involving such particles dominate the axino production. For $T_{\text{R}} \gg m_{\tilde{q}}, m_{\tilde{g}}$, Y^{scat} grows linearly as T_{R} becomes larger. In contrast, the decay contribution above the gluino mass

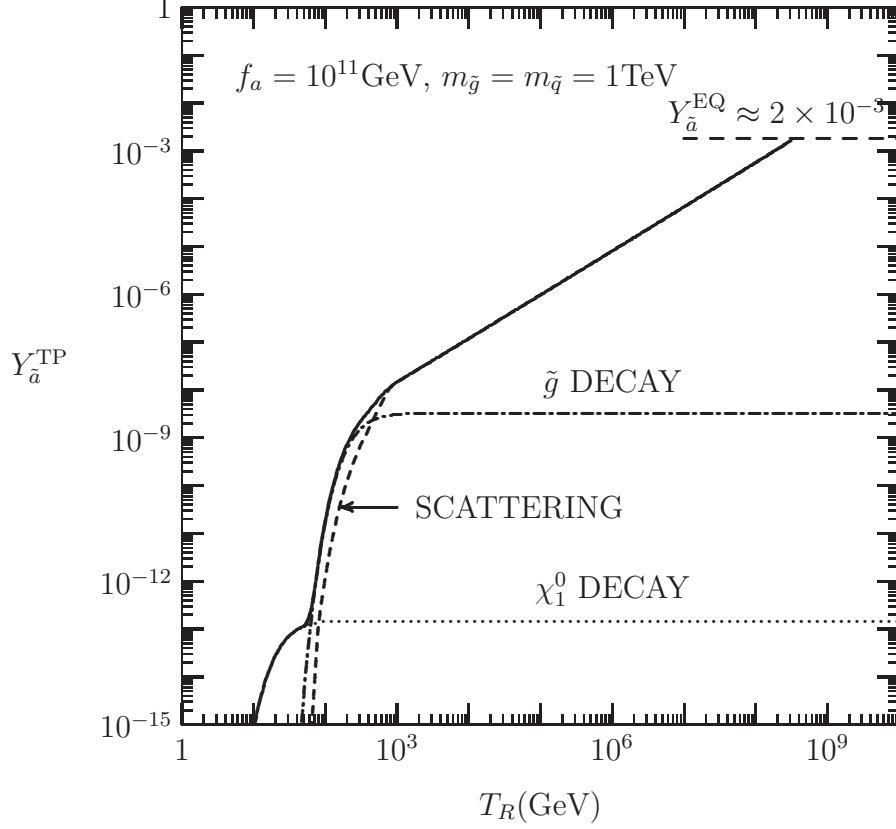


Figure 1: Y_a^{TP} as a function of T_R for representative values of $f_a = 10^{11}\text{GeV}$ and $m_{\tilde{g}} = m_{\tilde{q}} = 1\text{TeV}$.

threshold, $Y^{\text{dec}} \simeq 5 \times 10^{-4} (M_P \Gamma_{\tilde{g}} / m_{\tilde{g}}^2)$, remains independent of T_R . At T_R roughly below the mass of the squarks and gluinos, their thermal population starts to become strongly suppressed by the Boltzmann factor $e^{-m/T}$, hence a distinct knee in the scattering contribution in Fig. 1. It is in this region that gluino decays (dash-dotted line) given by Eq. (4) become dominant before they also become suppressed by the Boltzmann factor due to the gluino mass. For $m_\chi \lesssim T_R \lesssim m_{\tilde{q}}, m_{\tilde{g}}$, the axino yield is well approximated by $Y^{\text{TP}} \approx Y^{\text{dec}} \simeq 5 \times 10^{-4} (M_P \Gamma_{\tilde{g}} / T_R^2) e^{-m_{\tilde{g}}/T_R}$, and depends sensitively on the reheating temperature.

At still lower temperatures the population of strongly interacting particles becomes so tiny that at $T_R \sim m_\chi$ neutralino decays start playing some role before they too become Boltzmann factor suppressed. We indicate this by plotting in Fig. 1 the contribution of the lightest neutralino (dotted line). It is clear that the values of Y_a^{TP} in this region are so small that, as we will see later, they will not play any role in further discussion. We therefore do not present the effect of the decay of the heavier neutralinos. Furthermore,

model-dependent dimension-four operators will change axino production cross section at lower $T_R \sim M_{\text{SUSY}}$ but will be suppressed at high temperatures. We have not studied this point yet.

We emphasize that axinos produced in this way are already out of equilibrium. Their number density is very much smaller than n_γ (except $T_R \sim 10^9$ GeV and above) and cross sections for axino re-annihilation into other particles are greatly suppressed. This is why in Eq. (2) we have neglected such processes. Nevertheless, even though axinos never reach equilibrium, their number density may be large enough to give $\Omega_{\tilde{a}} \sim 1$ for large enough axino masses (keV to GeV range) as we will see later.

3.2 Non-Thermal Production

The mechanism for non-thermal production (NTP) that we will consider works as follows. Consider some lightest ordinary superpartner (LOSP). Because axino LSP couplings to everything else are suppressed by $1/f_a$, as the Universe cools down, all heavier SUSY partners will first cascade-decay to the LOSP. The LOSPs then freeze out of thermal equilibrium and subsequently decay into axinos.

A natural (although not unique), candidate for the LOSP is the lightest neutralino. For example, in models employing full unification of superpartner masses (like the CMSSM/mSUGRA), a mechanism of radiative electroweak symmetry breaking typically implies $\mu^2 \gg M_1^2$, where M_1 is the bino mass parameter. As a result, the bino-like neutralino often emerges as the lightest ordinary superpartner[9, 10, 11].

In the following we will assume that LOSP is the neutralino. It can decay to the axino and photon $\chi \rightarrow \tilde{a}\gamma$ with the rate[1, 2]

$$\Gamma(\chi \rightarrow \tilde{a}\gamma) = \frac{\alpha_{em}^2 C_{a\chi\gamma}^2}{128\pi^3} \frac{m_\chi^3}{(f_a/N)^2} \left(1 - \frac{m_{\tilde{a}}^2}{m_\chi^2}\right)^3. \quad (6)$$

Here α_{em} is the electromagnetic coupling strength, $C_{a\chi\gamma} = (C_{aYY}/\cos\theta_W)Z_{11}$, with Z_{11} standing for the bino part of the lightest neutralino. (We use the basis $\chi_i = Z_{i1}\tilde{B} + Z_{i2}\tilde{W}_3 + Z_{i3}\tilde{H}_b^0 + Z_{i4}\tilde{H}_t^0$ ($i = 1, 2, 3, 4$) of the respective fermionic partners (denoted by a tilde) of the electrically neutral gauge bosons B and W_3 , and the MSSM Higgs bosons H_b and H_t .)

The corresponding lifetime can be written as

$$\tau(\chi \rightarrow \tilde{a}\gamma) = \frac{0.33 \text{ sec}}{C_{aYY}^2 Z_{11}^2} \left(\frac{\alpha_{em}^2}{1/128}\right)^{-2} \left(\frac{f_a/N}{10^{11} \text{ GeV}}\right)^2 \left(\frac{100 \text{ GeV}}{m_\chi}\right)^3 \left(1 - \frac{m_{\tilde{a}}^2}{m_\chi^2}\right)^{-3}. \quad (7)$$

For large enough neutralino mass, an additional decay channel into axino and Z boson opens up but is always subdominant relative to $\chi \rightarrow \tilde{a}\gamma$ because of both the phase-space suppression and the additional factor of $\tan^2\theta_W$. As a result, even at $m_\chi \gg m_Z, m_{\tilde{a}}$, $\tau(\chi \rightarrow \tilde{a}Z) \simeq 3.35 \tau(\chi \rightarrow \tilde{a}\gamma)$. It is also clear that the neutralino

lifetime rapidly decreases with its mass ($\sim 1/m_\chi^3$). On the other hand, if the neutralino is not mostly a bino, its decay will be suppressed by the Z_{11} - factor in $C_{a\chi\gamma}$.

Other decay channels are the decay into axino and Standard Model fermion pairs through virtual photon or Z but they are negligible compared with the previous ones. We will discuss them later since, for a low neutralino mass, *i.e.*, long lifetime, they can, even if subdominant, produce dangerous hadronic showers during and after nucleosynthesis.

Additionally, in the DFSZ type of models, there exists an additional Higgs-higgsino-axino couplings, which may open up other channels[2]. These are model-dependent and I will not discuss them here.

3.3 Constraints

Several nontrivial conditions have to be satisfied in order for axinos to be a viable CDM candidate. First, we will expect their relic abundance to be large enough, $\Omega_{\tilde{a}}h^2 \simeq 0.2$. This obvious condition will have strong impact on other bounds. Next, the axinos generated through both TP and NTP will in most cases be initially relativistic. We will therefore require that they become non-relativistic, or cold, much before the era of matter dominance. Furthermore, since NTP axinos will be produced near the time of BBN, we will require that they do not contribute too much relativistic energy density to radiation during BBN. Finally, axino production associated decay products will often result in electromagnetic and hadronic showers which, if too large, would cause too much destruction of light elements. In deriving all of these conditions, except for the first one, the lifetime of the parent LOSP will be of crucial importance.

A detailed discussion of the bounds would take too much time, and space, that is available. I will therefore merely summarize the relevant results. First, the condition that the axinos give a dominant contribution to the matter density at the present time can be expressed as $m_{\tilde{a}}Y_{\tilde{a}} \simeq 0.72 \text{ eV } (\Omega_{\tilde{a}}h^2/0.2)$ which applies to both TP and NTP relics. It is worth mentioning here that, for the initial population of axinos, the yield at decoupling is approximately $Y_{\tilde{a}} \simeq Y_{\tilde{a}}^{\text{EQ}} \simeq 2 \times 10^{-3}$ which gives $m_{\tilde{a}} \simeq 0.36 \text{ keV } (\Omega_{\tilde{a}}h^2/0.2)$. This is an updated value for the RTW bound. Next, we want to determine the temperature of the Universe at which the axinos will become non-relativistic. In nearly all cases axinos are initially relativistic and, due to expansion, become non-relativistic at some later epoch which depends on their mass and production mechanism. In the case of TP, axinos are not in thermal equilibrium but, since they are produced in kinetic equilibrium with the thermal bath, their momenta will have a thermal spectrum. They will become non-relativistic when the thermal bath temperature reaches the axino mass, $T_{\text{NR}} \simeq m_{\tilde{a}}$.

NTP axinos generated through out-of-equilibrium neutralino decays will be produced basically monochromatically, all with the same energy roughly given by $m_\chi/2$, unless they are nearly mass-degenerate with the neutralinos. This is so because the neutralinos, when they decay, are themselves already non-relativistic. Thus, due to momentum red-

shift, axinos will become non-relativistic only at a later time, when $p(T_{\text{NR}}) \simeq m_{\tilde{a}}$. The temperature T_{NR} can be expressed as[2]

$$T_{\text{NR}} = 4.2 \times 10^{-5} m_{\tilde{a}} C_{aYY} Z_{11} (m_{\chi}/100 \text{ GeV})^{1/2} (10^{11} \text{ GeV}/f_a/N). \quad (8)$$

This epoch has to be compared to the matter-radiation equality epoch given by $T_{\text{eq}} = 1.1 \text{ eV} (\Omega_{\tilde{a}} h^2/0.2)$ which holds for both thermal and non-thermal production. In the TP case one can easily see that $T_{\text{NR}} > T_{\text{eq}}$ is satisfied for any interesting range of $m_{\tilde{a}}$. In the case of NTP the condition $T_{\text{NR}} \gg T_{\text{eq}}$ is satisfied for

$$m_{\tilde{a}} \gg 27 \text{ keV} \frac{1}{C_{aYY} Z_{11}} \left(\frac{100 \text{ GeV}}{m_{\chi}} \right)^{1/2} \left(\frac{f_a/N}{10^{11} \text{ GeV}} \right) \left(\frac{\Omega_{\tilde{a}} h^2}{0.2} \right). \quad (9)$$

If axinos were lighter than the bound (9), then the point of radiation-matter equality would be shifted to a later time around T_{NR} . Note that in this case axino would not constitute cold, but warm or hot dark matter. In the NTP case discussed here other constraints would however require the axino mass to be larger than the above bound, so that we can discard this possibility.

BBN predictions provide further important constraints on axinos as relics. In the case of non-thermal production most axinos will be produced only shortly before nucleosynthesis and, being still relativistic, may dump too much to the energy density during the formation of light elements. In order not to affect the Universe's expansion during BBN, axino contribution to the energy density should satisfy $\rho_{\tilde{a}}/\rho_{\nu} \leq \delta N_{\nu}$, where ρ_{ν} is the energy density of one neutrino species. Agreement with observations of light elements requires $\delta N_{\nu} = 0.2 - 1$. This leads to[2]

$$m_{\tilde{a}} \gtrsim 181 \text{ keV} \frac{1}{\delta N_{\nu}} \frac{1}{C_{aYY} Z_{11}} \left(\frac{100 \text{ GeV}}{m_{\chi}} \right)^{1/2} \left(\frac{f_a/N}{10^{11} \text{ GeV}} \right) \left(\frac{\Omega_{\tilde{a}} h^2}{0.2} \right). \quad (10)$$

Finally, photons and quark-pairs produced in NTP decays of neutralinos, if produced during or after BBN, may lead to a significant depletion of primordial elements. One often applies a crude constraint that the lifetime should be less than about 1 second which in our case would provide a lower bound on m_{χ} . First, photons produced in reaction $\chi \rightarrow \tilde{a}\gamma$ carry a large amount of energy, roughly $m_{\chi}/2$. If the decay takes place before BBN, the photon will rapidly thermalize via multiple scatterings from background electrons and positrons. The process will be particularly efficient at plasma temperatures above 1 MeV which is the threshold for background $e\bar{e}$ pair annihilation, and which, incidentally, coincides with time of about 1 second. But a closer examination[12] shows that also scattering with the high energy tail of the CMBR thermalize photons very efficiently and so the decay lifetime into photons can be as large as 10^4 sec. By comparing this with Eq. (7) we find that, in the gaugino regime, this can be easily satisfied for $m_{\chi} < m_Z$. It is only in a nearly pure higgsino case and mass of tens of GeV that the bound would become constraining. We are not interested in such light higgsinos for other reasons, as will be explained later.

A much more stringent constraint comes from considering hadronic showers from $q\bar{q}$ -pairs. These will be produced through a virtual photon and Z exchange, and, above the kinematic threshold for $\chi \rightarrow \tilde{a}Z$, also through the exchange of a real Z -boson. Here the discussion is somewhat more involved and the resulting constraint strongly depends on m_χ . One can show[2] that at the end one gets roughly $m_{\tilde{a}} \gtrsim 360$ MeV for $m_\chi \lesssim 60$ GeV which gives the strongest bound so far. However, the bound on $m_{\tilde{a}}$ decreases nearly linearly with m_χ and disappears completely for $m_\chi \gtrsim 150$ GeV.

In summary, a lower bound $m_{\tilde{a}} \gtrsim \mathcal{O}(300 \text{ keV})$ arises from either requiring the axinos to be cold at the time of matter dominance or that they do not contribute too much to the relativistic energy density during BBN. The constraint from hadronic destruction of light elements can be as strong as $m_{\tilde{a}} \gtrsim 360$ MeV (in the relatively light bino case) but it is highly model-dependent and disappears for larger m_χ .

3.4 Relic Abundance from Thermal and Non-Thermal Production

In the TP case the axino yield is primarily determined by the reheating temperature. For large enough T_R ($T_R \gg m_{\tilde{g}}, m_{\tilde{q}}$), it is proportional to T_R/f_a^2 . In contrast, the NTP axino yield is for the most part independent of T_R (so long as $T_R \gg T_f$, the neutralino freezeout temperature). In the NTP case, the yield of axinos is just the same as that of the decaying neutralinos. This leads to[1] $\Omega_{\tilde{a}} h^2 = m_{\tilde{a}}/m_\chi \Omega_\chi h^2$, where $\Omega_\chi h^2$ stands for the abundance that the neutralinos would have had today had they not decayed into axinos.

In order to be able to compare both production mechanisms, we will therefore fix the neutralino mass at some typical value. Furthermore we will map out a cosmologically interesting range of axino masses for which $\Omega_{\tilde{a}}^{\text{NTP}} \sim 1$. Our results are presented in Fig. 2 in the case of a nearly pure bino. We also fix $m_\chi = 100$ GeV and $f_a = 10^{11}$ GeV. The dark region is derived in the following way. It is well known that $\Omega_\chi h^2$ can take a wide range of values spanning several orders of magnitude. In the framework of the MSSM, which we have adopted, global scans give $\Omega_\chi h^2 \lesssim 10^4$ in the bino region at $m_\chi \lesssim 100$ GeV. (This limit decreases roughly linearly (on a log-log scale) down to $\sim 10^3$ at $m_\chi \simeq 400$ GeV.) For $m_\chi = 100$ GeV we find that the expectation $\Omega_{\tilde{a}}^{\text{NTP}} h^2 \simeq 1$ gives

$$10 \text{ MeV} \lesssim m_{\tilde{a}} \lesssim m_\chi. \quad (11)$$

We note, however, that the upper bound $\Omega_\chi h^2 \lesssim 10^4$ comes from allowing very large M_{SUSY} (*i.e.*, sfermion and heavy Higgs masses) in the range of tens of TeV. Restricting all SUSY mass parameter below about 1 TeV reduces $\Omega_\chi h^2$ below 10^2 and, accordingly, increases the lower bound $m_{\tilde{a}} \gtrsim 1$ GeV. Still, for the sake of generality, we have the much more generous bound (11) in Fig. 2 but marked a low range of $m_{\tilde{a}}$ with a light grey band to indicate the above point.

Likewise, for reheating temperatures just above T_f standard estimates of $\Omega_\chi h^2$ become questionable. We have therefore indicated this range of T_R with again a light grey color. It has also been recently pointed out[13] that even in the case of very low reheating temperatures T_R below the LOSP freezeout temperature, a significant population of them will be generated during the reheating phase. Such LOSPs would then also decay into axinos as above. We have not considered such cases in our analysis and accordingly left the region $T_R < T_f$ blank even though in principle we would expect some sizeable range of $\Omega_{\tilde{a}} h^2$ there.

We can see that for large T_R , the TP mechanism is more important than the NTP one, as expected. Note also that in the TP case the cosmologically favored region ($0.2 \lesssim \Omega_{\tilde{a}} h^2 \lesssim 0.4$) would form a very narrow strip (not indicated in Fig. 2) just below the $\Omega_{\tilde{a}}^{\text{TP}} = 1$ -boundary. In contrast, the NTP mechanism can give the cosmologically interesting range of the axino relic abundance for a relatively wide range of $m_{\tilde{a}}$ so long as $T_R \lesssim 5 \times 10^4 \text{ GeV}$. Perhaps in this sense, the NTP mechanism can be considered as somewhat more robust.

3.5 Conclusions

The intriguing possibility that the axino is the LSP and dark matter possesses a number of very distinct features which makes this case very different from those of both the neutralino and the gravitino. In particular, the axino can be a cold DM WIMP for a rather wide range of masses in the MeV to GeV range and for relatively low reheating temperatures $T_R \lesssim 5 \times 10^4 \text{ GeV}$. As T_R increases, thermal production of axinos starts dominating over non-thermal production and the axino typically becomes a warm DM relic with a mass broadly in a keV range. In contrast, the neutralino is typically a cold DM WIMP.

Low reheating temperatures would favor baryogenesis at the electroweak scale. It would also alleviate the nagging “gravitino problem”. If additionally it is the axino that is the LSP and the gravitino is the NLSP, the gravitino problem is resolved altogether for both low and high T_R .

Phenomenologically, one faces a well-justified possibility that the bound $\Omega_\chi h^2 < 1$, which is often imposed in constraining a SUSY parameter space, may be readily avoided. In fact, the range $\Omega_\chi h^2 \gg 1$ (and with it typically large masses of superpartners) would now be favored if axino is to be a dominant component of DM in the Universe. Furthermore, the lightest ordinary superpartner could either be neutral or charged but would appear stable in collider searches.

The axino, with its exceedingly tiny coupling to other matter, will be a real challenge to experimentalist. It is much more plausible that a supersymmetric particle and the axion will be found first. Unless the neutralino (or some other WIMP) is detected in DM searches, the axino will remain an attractive and robust candidate for solving the outstanding puzzle of the nature of dark matter in the Universe.

References

- [1] L. Covi, J.E. Kim and L. Roszkowski, Phys. Rev. Lett. **82**, 4180 (1999).
- [2] L. Covi, H.B. Kim, J.E. Kim and L. Roszkowski, hep-ph/0101009.
- [3] J.E. Kim, Phys. Rev. Lett. **43**, 103 (1979); M.A. Shifman, V.I. Vainstein, and V.I. Zakharov, Nucl. Phys. **B166**, 4933 (1980).
- [4] M. Dine, W. Fischler, and M. Srednicki, Phys. Lett. **B104**, 99 (1981); A.P. Zhitnitskii, Sov. J. Nucl. Phys. **31**, 260 (1980).
- [5] J.E. Kim, Phys. Rep. **150**, 1 (1987); M.S. Turner, Phys. Rep. **197**, 67 (1990); G.G. Raffelt, Phys. Rep. **198**, 1 (1990); P. Sikivie, hep-ph/0002154.
- [6] K. Tamvakis and D. Wyler, Phys. Lett. **B112**, 451 (1982).
- [7] K. Rajagopal, M. S. Turner, and F. Wilczek, Nucl. Phys. **B358**, 447 (1991).
- [8] E.J. Chun, J.E. Kim and H. P. Nilles, Phys. Lett. **B287**, 123 (1992).
- [9] P. Nath and R. Arnowitt, Phys. Rev. Lett. **69**, 725 (92).
- [10] R.G. Roberts and L. Roszkowski, Phys. Lett. **B309**, 329 (1993).
- [11] G.L. Kane, C. Kolda, L. Roszkowski, and J.D. Wells, Phys. Rev. **D49**, 6173 (1994).
- [12] J. Ellis, *et al.*, Nucl. Phys. **B373**, 399 (1992).
- [13] G.F. Giudice, E.W. Kolb, and A. Riotto, hep-ph/0005123.

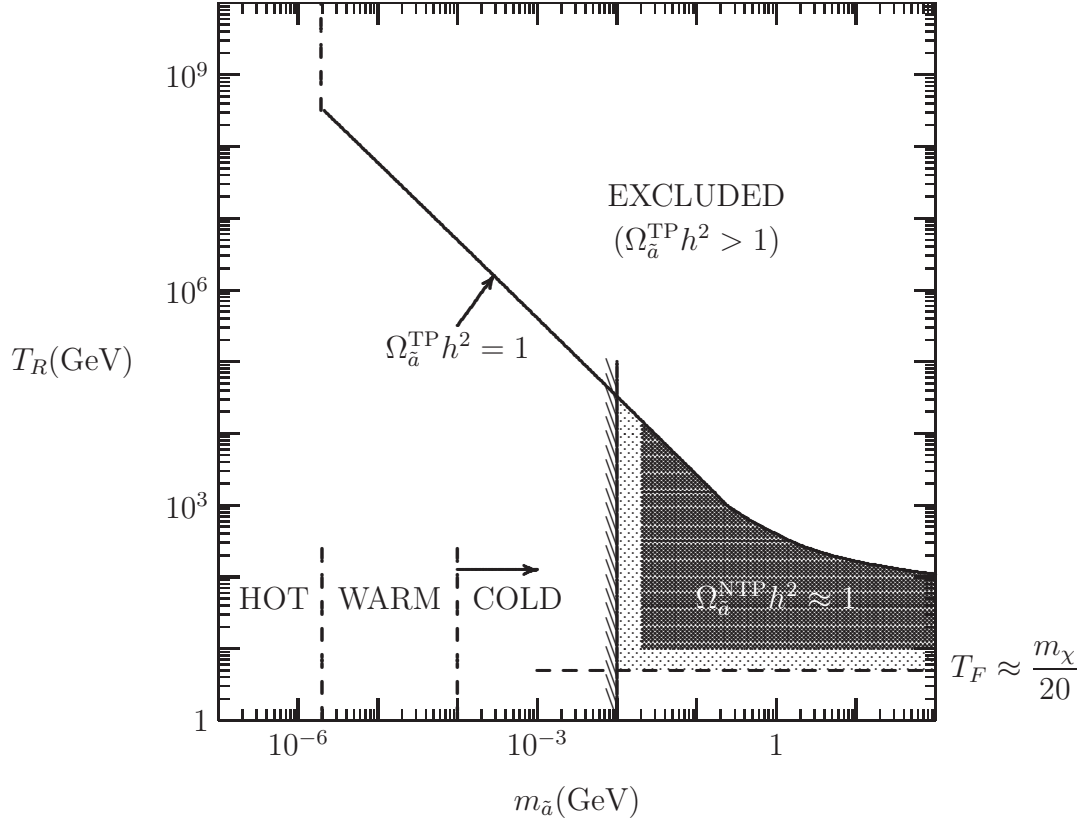


Figure 2: The thick solid line gives the upper bound from thermal production on the reheating temperature as a function of the axino mass. The dark region is the region where non-thermal production can give cosmologically interesting results ($\Omega_{\tilde{a}}^{\text{NTP}} h^2 \simeq 1$) as explained in the text. We assume a bino-like neutralino with $m_\chi = 100$ GeV and $f_a = 10^{11}$ GeV. The region of $T_R \gtrsim T_f$ is somewhat uncertain and has been denoted with light-grey color. A sizeable abundance of neutralinos (and therefore axinos) is expected also for $T_R \lesssim T_f$ but has not been calculated. The vertical light-grey band indicates that a low range of $m_{\tilde{a}}$ corresponds to allowing SM superpartner masses in the multi-TeV range, as discussed in the text. Division of hot, warm and cold dark matter by the axino mass shown in lower left part is for axinos from non-thermal production.